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LABORATORY FOR THE STUDY OF SPACE RADIATION EFFECTS

By Dr. John E. Duberg* and Emanuel Rind**

INTRODUCTION

The Langley Research Center of NASA, because of its programs involving space vehicles and the equipments therein, has had a special interest in the space environment insofar as it influences the design of space vehicle systems. Of the many hostile aspects of this environment, perhaps the most significant is the particulate radiation associated with cosmic rays, solar flares, and that magnetically trapped near the earth in the radiation belts. The Langley Research Center is now constructing a Space Radiation Effects Laboratory for the purpose of simulating the particulate space radiation environment and by this means providing the means by which the tests and fundamental studies can be made in this problem area.

SUMMARY OF THE SPACE PARTICULATE RADIATION

A brief summary of our knowledge of flux and energy level of particulate radiation in space is given in table I.[1,2]

TABLE I.- SUMMARY OF THE PROTONS AND ELECTRONS IN SPACE

PROTONS

Low energy	High energy
120 Kev $< E <$ 4.5 Mev	30 Mev $< E <$ 700 Mev
Flux $\approx 10^8$ p/cm^2/sec	Flux $\approx 2 - 4 \times 10^4$ p/cm^2/sec

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[1]T. Foelsche. Radiation Doses in Interplanetary Flight. Presented at the Ninth Annual American Astronautical Society Meeting of the Interplanetary Missions Conference, Jan. 15-16-17, 1963 at Los Angeles, California.

[2]L. R. Davis, and J. M. Williamson. Trapped Protons and Electrons Between Two and Twelve Earth's Radii. Presented at Symposium on Explorer XII, NASA Goddard Space Flight Center, Greenbelt, Maryland, Jan. 1962.

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Intensity can vary by a factor of 2 to 3 with solar activity.

SOLAR FLARES

Low energy	High energy
$E < 40$ Mev	$E \to 10$ Bev
Flux $\approx 10^5 - 10^6$ protons/cm^2/sec	

ELECTRONS

Low energy	High energy
110 Kev $< E <$ 1.6 Mev	1.6 Mev $< E <$ 5 Mev
Flux $< 10^8$ e/cm^2/sec	Flux $< 10^5$ e/cm^2/sec
$E >$ 10 Kev	$E >$ 5 Mev
Flux $\approx 10^9$ e/cm^2/sec	Flux $< 10^3$ e/cm^2/sec

Flux can vary by a factor of 50 to 100 with solar activity.

Table I summarizes data obtained in space flight through Explorer XII. It does not include the changes caused by a high-altitude nuclear detonation in 1962. The high-energy protons are generally encountered in the inner radiation region at about 10,000 kilometers from the earth's center whereas the low-energy protons are found between 20,000 and 30,000 kilometers.

The maximum integral energy flux of the solar flares varies between 10^5 to 10^6 protons/cm^2/sec with energies ranging from Kevs to about 10 Bev. By far, the largest number of these protons have energies somewhat less than one Bev.

The natural belt electrons have their highest intensities (between 10^8 and 10^9 e/cm^2/sec) at about 16,000 to 27,000 kilometers as measured from the earth's center. The electrons of the manmade belt had measured peak intensities greater than 10^9 e/cm^2/sec and occurred at about 10,500 kilometers. The energies of both the manmade and naturally occurring electrons extend from a few Kev into the Mev range.

MEANS FOR SIMULATING THE SPACE RADIATION ENVIRONMENT

As the previous summary of the space environment indicates, a facility which can produce protons from low energies to energies below a Bev and electrons from the Kev range to 10 Mev with suitable fluxes would simulate most of the known space particulate radiation. In order to avoid years of development time in establishing the laboratory, it was decided to duplicate an existing proven, proton accelerator design which had the desired energy and flux capability. The choice based on availability was narrowed to frequency-modulated cyclotrons and alternating gradient synchrotrons. The synchrocyclotron was chosen because its external flux was adequate for our purposes, whereas the external flux of the synchrotron machine was lower by about two orders of magnitude. Considerations of down time, beam extraction, and overall proven reliability were additional factors in favor of the synchrocyclotron.

There are four synchrocyclotrons in the world with energies of about 0.6 Bev or greater. The two behind the iron curtain were not considered. The other two are the machine at Berkeley, California (0.76 Bev) and the machine at CERN, Geneva, Switzerland (0.6 Bev). The CERN machine was designed from its concept for its stated energy and incorporated the most modern ideas of the day. The Berkeley machine has been redesigned and altered to bring it up from its initial lower energies to its present level and any design improvements of it and other existing accelerators were considered in the design of the CERN machine. Since the CERN machine was the most modern, met the energy and flux requirements, and had a very good operational history, it was chosen.

The electron requirements were satisfied by a Dynamitron with an energy range from about 500 Kev to 3 Mev and linac from 2 to 16 Mev. The linac has provision for extending the energy range to 30 Mev.

PLAN OF THE SPACE RADIATION EFFECTS LABORATORY

The floor plan of the Space Radiation Effects Laboratory is divided into three major areas as shown in figure 1. These are the experimental test and beam handling area, the test setup area, and the support building. The experimental test and beam handling area consists of two independent target areas, the electron accelerator caves with their target areas, the proton accelerator cave, and the magnet hall which will contain the beam transport and handling for the proton accelerator. The two target areas are about 37 by 26 feet each and these dimensions may be changed by moving the walls. One target area is arranged for receiving a combined electron and proton beam. Sufficient space has been allowed around the accelerators to permit ready access and normal maintenance without the inconvenience of moving shielding. Very large targets may be irradiated by piping the beam directly down the magnet hall to an externally setup test area. The shielding walls are about 17 to 24 feet thick and where short particle lifetimes and space requirements dictate, heavy concrete and/or steel walls are used. Overhead shielding is provided to reduce undesired radiation effects from above. The proposed physics test areas will be so isolated as to give low background radiation, thus permitting the performance of very refined experiments. The proposed neutron-meson area will be adjacent to the cyclotron cave separated by a relatively thin steel and heavy concrete wall. The test setup area allows setups and measurements to be made without disturbance prior to installation into the target areas. Large vertical lift doors separate the target area from the setup area. The dimensions of the experimental test and setup areas are approximately 240 feet by 143 feet covering a floor area of approximately 33,000 sq ft.

A section view of the Experimental Building, taken through the synchrocyclotron cave, is shown in figure 2. The two 25-ton capacity crane hooks service the accelerator caves, test setup area, and target areas. The utility tunnel will contain the electrical cables to the various experimental areas and support building.

The support building is located next to the setup area which separates it from the experimental test area. It consists of two floors and a basement and will contain the control room and monitoring system for the accelerators, laboratory space, shop facilities, office space, counting areas, etc. Its size is 168 by 71 feet with a total floor area of approximately 21,000 square feet.

An architect's rendering of the Space Radiation Effects Laboratory is shown in figure 3. The site of the laboratory is located in the city of Newport News, Virginia, within 10 miles of the Langley Research Center. The site contains approximately 100 acres.

PROTON IRRADIATION SYSTEM

Dimensions and Capabilities

The CERN accelerator which is the basis of the SREL accelerator is a 600-Mev frequency-modulated synchrocyclotron with a magnet weighing about 2,500 tons. It is approximately 36 feet wide, 21.3 feet deep, and 20 feet high. The magnet gap varies from 17.7 inches in the center to 14.7 inches at the outer edge.[3] The magnet coils are made of about 333 turns each of rectangular, hollow aluminum, are water cooled and operate at about 1.2×10^6 ampere turns.

The radio-frequency system uses a water-cooled tuning-fork modulator which modulates the r-f frequency between 29 and 16.5 megacycles at 55 cps with Dee voltages varying from 6 kilovolts to 25 kilovolts.[4]

The vacuum system using two roughing and two 32-inch oil diffusion pumps provides a vacuum of about 10^{-6} Torr.

The ion source is a cold cathode type which receives a 1,000-volt d.c. pulse at the repetition frequency of the radio-frequency system and at a controllable phase.

The internal beam current is over 0.3 microamp and the extraction efficiency is about 10 percent.

BEAM TRANSPORT SYSTEM

The beam system will have at least two extraction systems at 600 and 180 Mev utilizing peeler-regenerator magnetic channel deflectors.[5] The external beam delivered to the target will be 10^{11} protons/sec with an energy spread less than plus or minus 1 percent. A proton beam transport system designed to handle 10^{12} protons per second at the above energy conditions shall, in addition, be capable of delivering continuously variable energy from 600 Mev to at least 100 Mev with a beam flux of not less than 10^{10} protons per second and an energy spread of not more than plus or minus 5 percent. The intensity distribution over the target will be less than plus or minus 5 percent and the beam area at the target will be continuously variable from 15 cm^2 to 900 cm^2. The transport system will clean the beam so that particles other than protons will not reach the target. The means for doing this, shown in figure 4, will be to trim the proton beam with

[3]Bengt Hedin, Design of CERN Synchro-Cyclotron Magnet, CERN 55-3, Synchro-Cyclotron Division, Jan. 14, 1955.

[4]W. Gentner, K. H. Schmitter, S. Kortleven, B. Bollée, and F. Krienen, the CERN 600 Mev Synchrocyclotron at Geneva, Phillips Technical Review, Vol. 22, 1960/61, No. 5, March 1961.

[5]Feasibility Study of the Procurement of a 600 Mev Synchrocyclotron on an Accelerated Schedule for the NASA. William M. Brobeck & Assoc. Report No. 200-90-1-R3, Nov. 8, 1961.

a collimator and focus with a pair of quadrupole magnets at the cyclotron exit. The beam will then be refocused by large aperture quadrupoles at focal points along the target path. A bending magnet in the cyclotron room is used to switch the beam into the magnet hall or the proposed proton area without destroying the quality of the beam. A degrader is then used as required to reduce the energy of the beam. The energy spread of the degraded beam is reduced by a collimator and the proton beam is deflected into a test area by a bending magnet-quadrapole-collimator set. The neutrons produced in the degrader are not deflected and are lost in the magnet room. The proton beam continues in its magnetic channel, is further degraded as needed, refocused, recollimated to reduce energy spread, and proceeds to irradiate the target. This system will be one of the most advanced beam handling systems representing the application of the latest theories and techniques available in achromatic beam transportation. Also available will be beam stops, a beam clipper to absorb those parts of the internal beam that have obtained excessive vertical oscillation, and a beam chopper which will enable the operator to vary the beam from zero to a maximum.

The internal target systems, shown in figure 5, will consist of a probe target for positioning targets at different radii in one azimuth. A universal target, trolley mounted, for positioning targets at various radii and azimuths, and eight flip targets for producing neutrons corresponding to proton energies from 110 to 600 Mev. Provision is also being made for installing vibrating targets.

THE ELECTRON ACCELERATION SYSTEM

Description and Capabilities

Two electron accelerators will be available. One a Dynamitron will have an energy range of 0.5 to 3 Mev with a beam current variable from 1 microamp to 10 milliamps. Capability will exist for scanning the beam from 7 to 12 cycles per second over a 24-inch length and provision will be made for switching to a positive ion source. The other accelerator, a linac, will have an energy range from 2 to 10 Mev with provision for extending the energy to 30 Mev. The average d.c. beam current will be continuously variable from zero to about 250 microamps at 3 and 10 Mev and about 1,000 microamps at 7 Mev with the intermediate energies having linearly corresponding current values. The beam pulse length will vary continously from 0.1 to 6 microseconds and stepwise to a pulse length of 0.01 microsecond. The 0.01-microsecond pulse will have a rise time of 5 nanoseconds, a duration of 10 nanoseconds, and a decay time of 5 nanoseconds. The pulse repetition rate will be continuously variable from 10 to 720 pulses per second. Single pulse operation will also be available.

THE ELECTRON BEAM TRANSPORT SYSTEM

The electron beam transport system will carry the electron beam to targets in their respective areas and also to a proton target area where a target may be irradiated with both electrons and protons. The system will accept electrons from 1 to 16 Mev with an energy spread of plus or minus 3 percent. A magnetic energy analyzing system will produce an electron beam at the proton target with an energy spread of plus or minus 1/2 percent for all energies accepted by the system. The beam area at the target will be continuously variable from 1 to 900 square centimeters. Capability will exist for producing neutron beams and X-rays using the electron beam. A schematic of the electron beam transport is shown in figure 6. Since the systems for the Dynamitron and the linac are almost identical, the one for the linac will be described. The electron beam is fed through a pair of quadrupole lenses, thence through a scatterer and bending magnet. All bending magnets are equipped with magnetic induction probes for monitoring the fields. If the beam is bent, it then passes through a quadrupole lens, a bending magnet, a pair of quadrupoles, a scintillation screen, secondary emission probe into the target test chamber. If the beam is not bent, it proceeds through a valve section beyond which it can be stopped by a remotely controlled beam stopper. If it is not stopped, it continues through a quadrupole pair, bending magnet, quadrupole, bending magnet, quadrupole pair, to a scintillation screen where it can be monitored. It then passes through some of the elements of the Dynamitron beam transport which may or may not be activated for focusing. The beam is then bent, channeled through another valve section, through a pair of quadrupoles, through collimators, detectors, into a Helmholtz coil, to the proton target test chamber.

THE TARGET CHAMBERS

Three test chambers will be provided which will be right circular cylinders 5 feet in diameter by 3 feet high with vacuum capability of 10^{-6} Torr with at least one going to 10^{-9} Torr. The size of the chambers makes possible combined environmental parameter testing such as radiation, pressure, and temperature. Water-cooling and electrical connections will exist for the targets.

OPERATION OF LABORATORY

The tentative operational plan for the SREL provides for William and Mary, the University of Virginia, and Virginia Polytechnical Institute organized as the Virginia Associates Research Center (VARC), to supply the operational personnel for SREL. The participating universities of VARC will also establish a basic physics research program sponsored by government grant, industry grants, or self-initiated. Other institutions requiring a facility with the available high-energy capability for basic research of SREL can cooperate with VARC. Programs for accelerator improvement and development may also be undertaken by VARC. The Langley Research Center will conduct the engineering, applications, and basic research phases associated with the space environment. Other NASA laboratories, government agencies, and industry under NASA contract can participate through the Langley Research Center.

RESEARCH PROGRAM

The research program to be conducted at the Space Radiation Effects Laboratory will include device testing, dosimetry, materials studies, sensor development, shielding studies, environmental contamination by radiation in a closed ecology, sputtering phenomena, activation, radiobiological research, health physics, basic physics, and, in general, investigation of problems and damage induced by space radiation. NASA, Langley Research Center, in anticipation of the activities of SREL has been developing its program of investigation and research in the area of the effects of particulate radiation. The program has made use of a number of fixed energy existing accelerators, covering the range from 22 to 440 Mev, at universities in the United States and Canada as well as national laboratories in the United States. To carry on these investigations and in preparing for those at SREL, theoretical and experimental work has been done in device testing,[6,7,8] dosimetry,[9] materials

[6] W. C. Hulten, W. C. Honaker, and J. L. Patterson. Irradiation Effects of 22 Mev and 240 Mev Protons on Several Transistors and Solar Cells. NASA TN D-718, 1961.

[7] W. C. Honaker. The Effects of Protons on Semi-Conductor Devices. Paper presented at the Symposium on Protection Against Radiation Hazards in Space. Gatlinburg, Tennessee, Nov. 5-7, 1962.

[8] W. C. Honaker, and F. R. Bryant. Irradiation Effects of 40 and 400 Mev Protons on Transistors. NASA TN D-1490, 1963.

[9] T. Foelsche. Current Estimates of Radiation Doses in Space. NASA TN D-1267, 1962.

studies,[10] and basic studies on semiconductor materials. Measurements are being made dynamically in beam as well as out of beam. A bremsstrahlung experiment for various electron energies and z numbers is currently underway. An ionization chamber and calorimetric technique for making beam measurements are being presently evaluated and radiation effects on polymers and elastomers as well as shielding studies have been initiated. To carry on these investigations as well as to prepare for those at the SREL, tools for measuring damage and analyzing radiation effects, which will include infra-red, electron paramagnetic and nuclear magnetic resonance, X-ray, mass and other spectroscopes, are being acquired and developed. Two grants to Rensselaer Polytechnical Institute for experimental work utilizing a high-energy electron accelerator have expanded the work effort within the program. One grant is for work on the effects of electrons, neutrons, gamma, and protons on semiconductor materials. The other is an experimental study for the analysis of primary recoils produced by high-energy electron irradiation on semiconductor materials. Contractual effort has also included a theoretical study of damage versus proton energy[11] and an experimental-theoretical investigation of neutron-proton damage correlation.[12]

CONCLUDING REMARKS

The primary purpose of the Space Radiation Effects Laboratory is to provide a facility in which investigations simulating the space environment can be performed and the results used to increase the reliability and safety of spacecraft and space missions. As the project has evolved, the Laboratory will serve a broader purpose. In one capacity, it will support an engineering research program aimed at increasing the reliability and safety of spacecraft and missions. In the other, it will provide our universities and colleges with the instruments by which they can conduct basic research in high-energy physics and thereby

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[10] T. G. James. Effect of Electron Irradiation on the Mechanical Properties of a Composite Foil for Inflatable Satellites. Paper presented at the Symposium on Protection Against Radiation Hazards in Space. Gatlinburg, Tennessee, Nov. 5-7, 1962.

[11] D. M. Arnold, J. A. Baicker, et al. Proton Damage in Semi-Conductor Devices. NASA, Langley Theoretical Study Contracted to RCA, Camden, New Jersey. Report due Feb. 1963.

[12] J. R. Belinski, E. H. Brooks, et al. Proton-Neutron Damage Correlation in Semi-Conductors. Report completed under NASA, Langley Contract No. NAS1-1595, June 1, 1962.

expand their graduate education program in this and other related fields. Thus, by providing a facility in which both these endeavors can be conducted, two vital needs are simultaneously fulfilled.

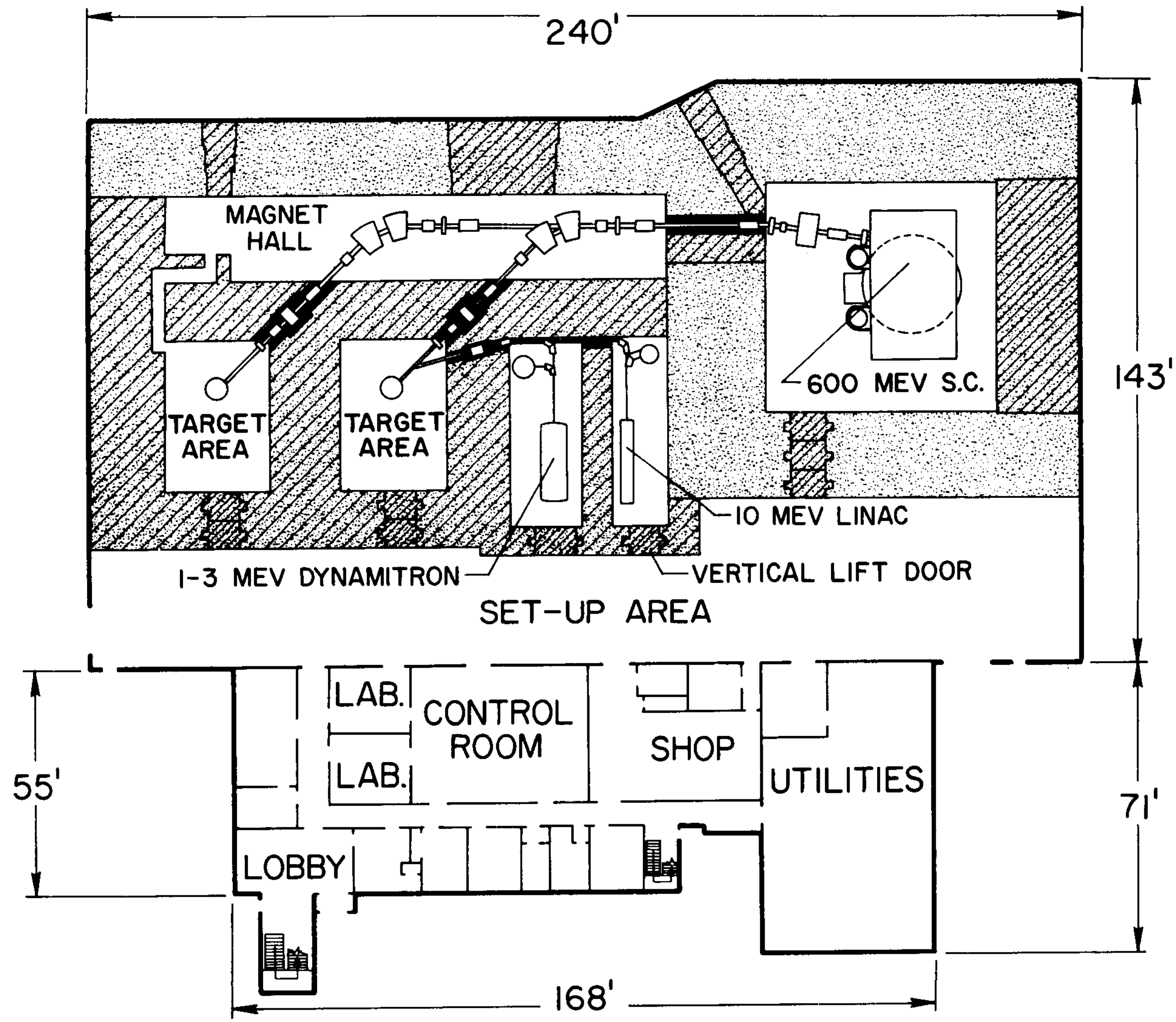

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Figure 1.- Plan of the Space Radiation Effects Laboratory.

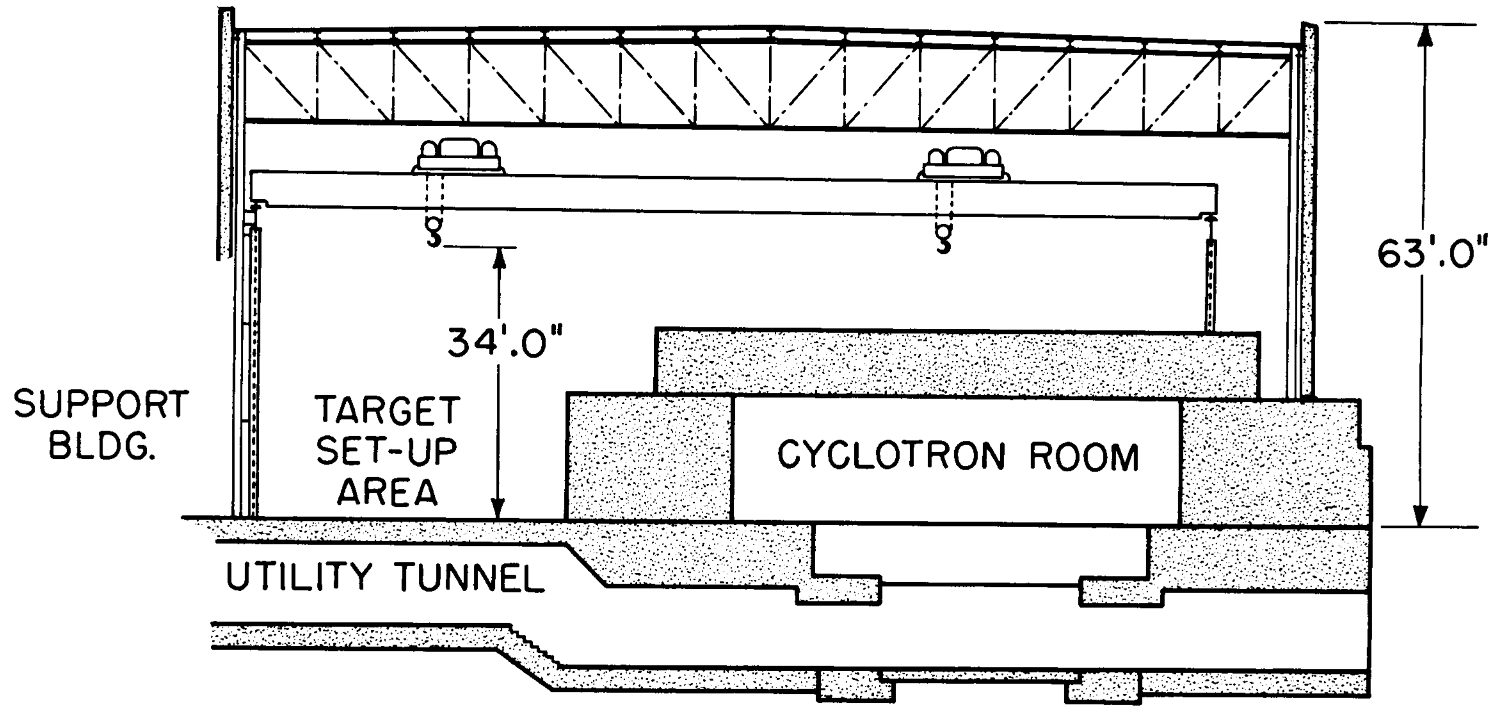

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Figure 2.- Section, Experimental Building.

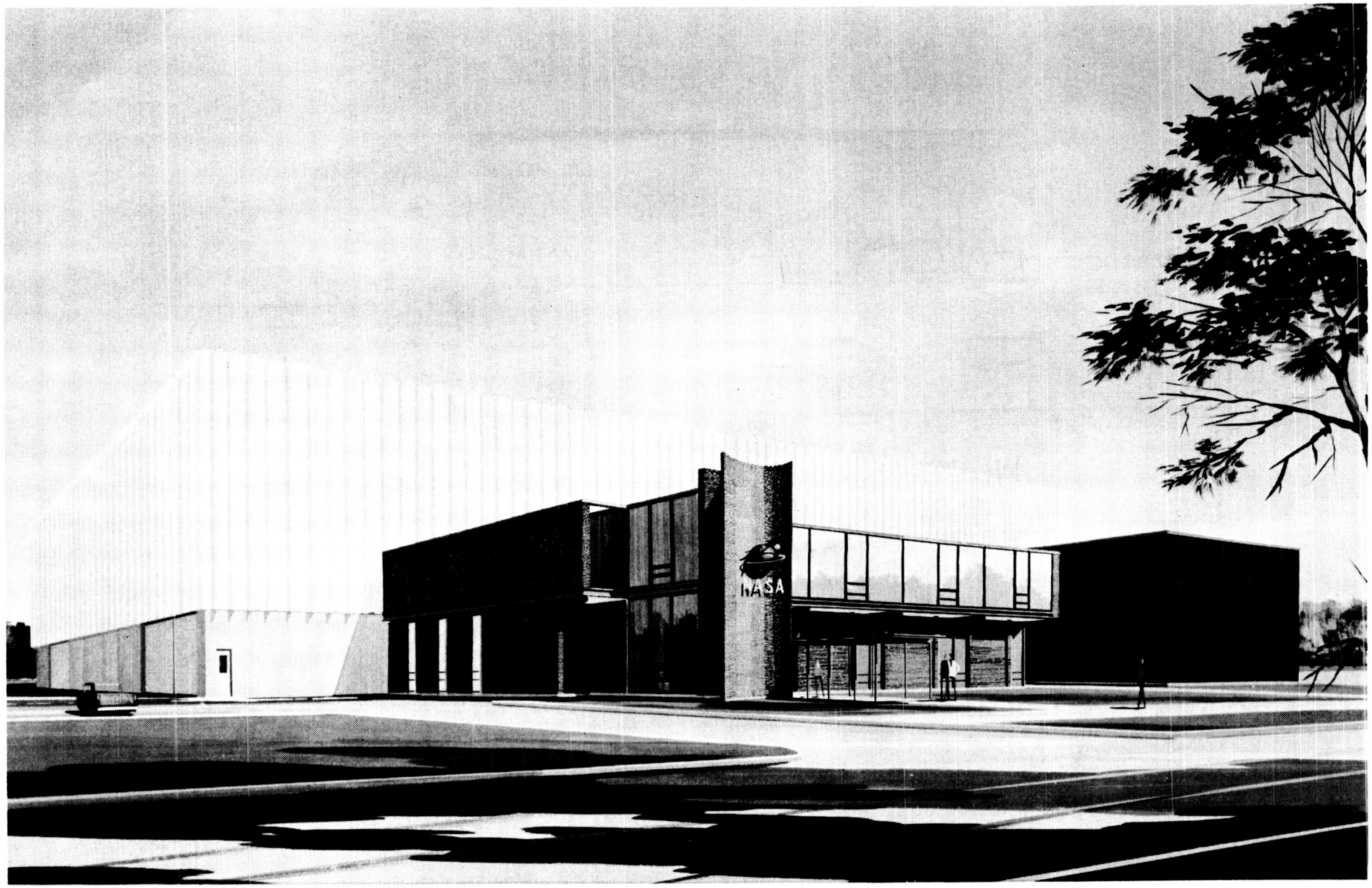

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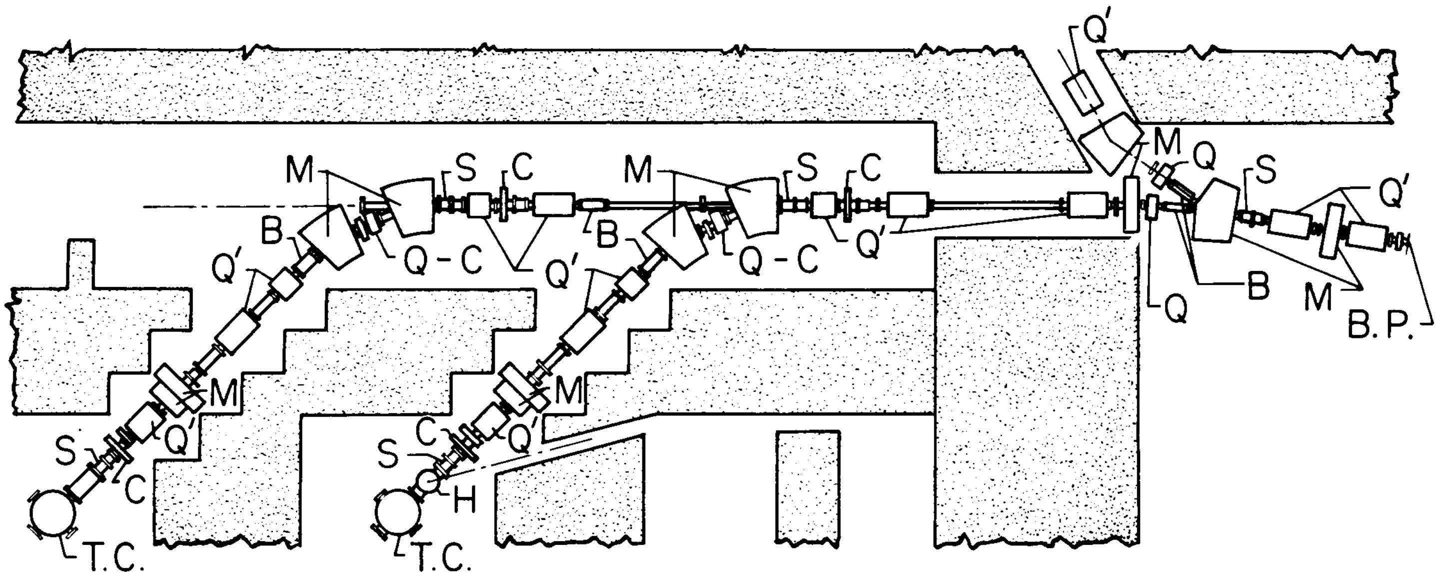
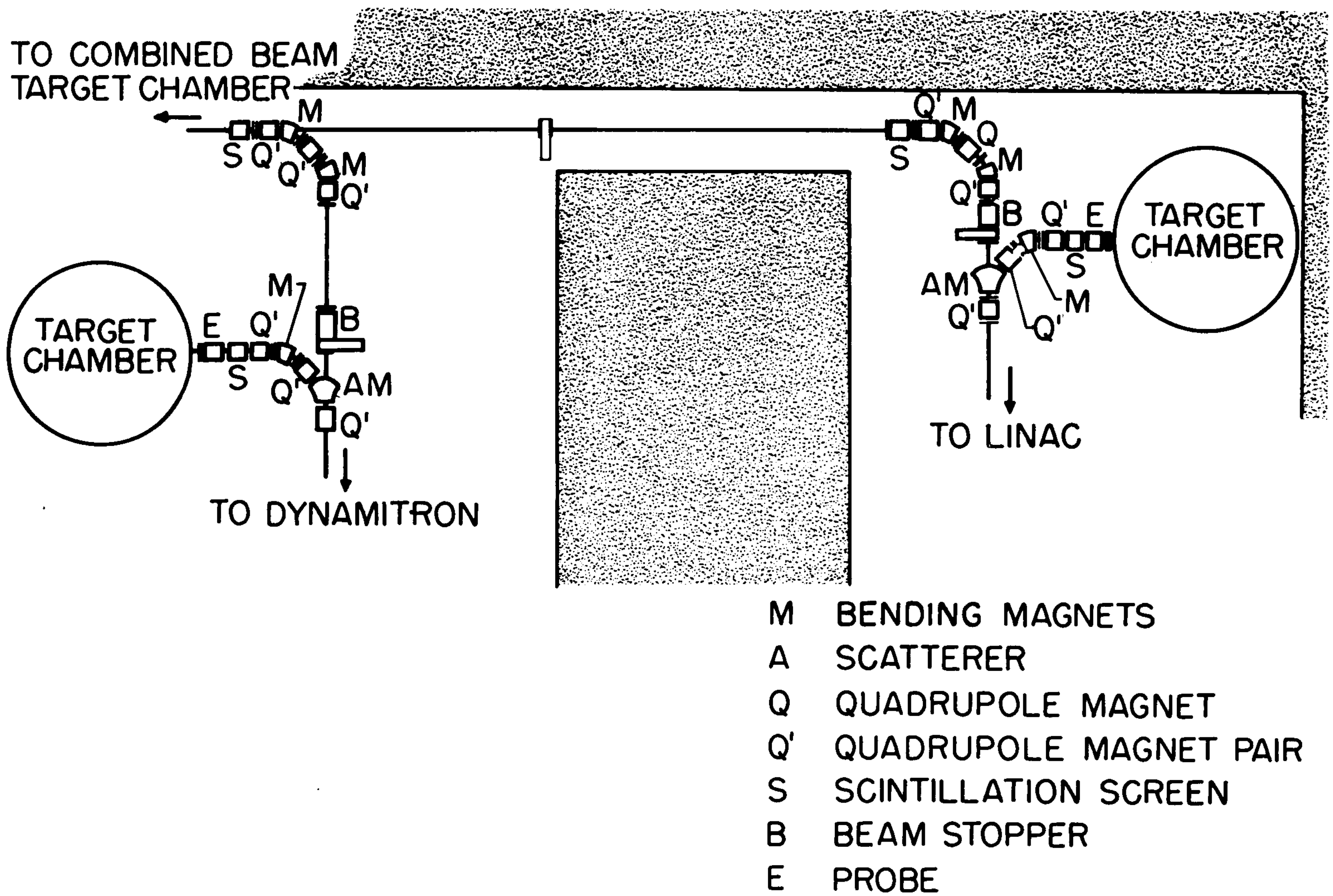
Figure 3.- Architect's perspective rendering of the Space Radiation Effects Laboratory.



M - BENDING OR STEERING MAGNET
Q′ - QUADRUPOLE MAGNET PAIR
Q - QUADRUPOLE MAGNETS
S - SCINTILLATION SCREEN
B - BEAM STOPPER
C - COLLIMATOR
H - HELMHOLTZ COIL
T.C. - TARGET CHAMBER
B.P. - BEAM PORT

NASA

Figure 4.- Schematic of Proton Beam Transport System.



NASA

Figure 6.- Schematic of Electron Beam Transport System.

NASA-Langley, 1963

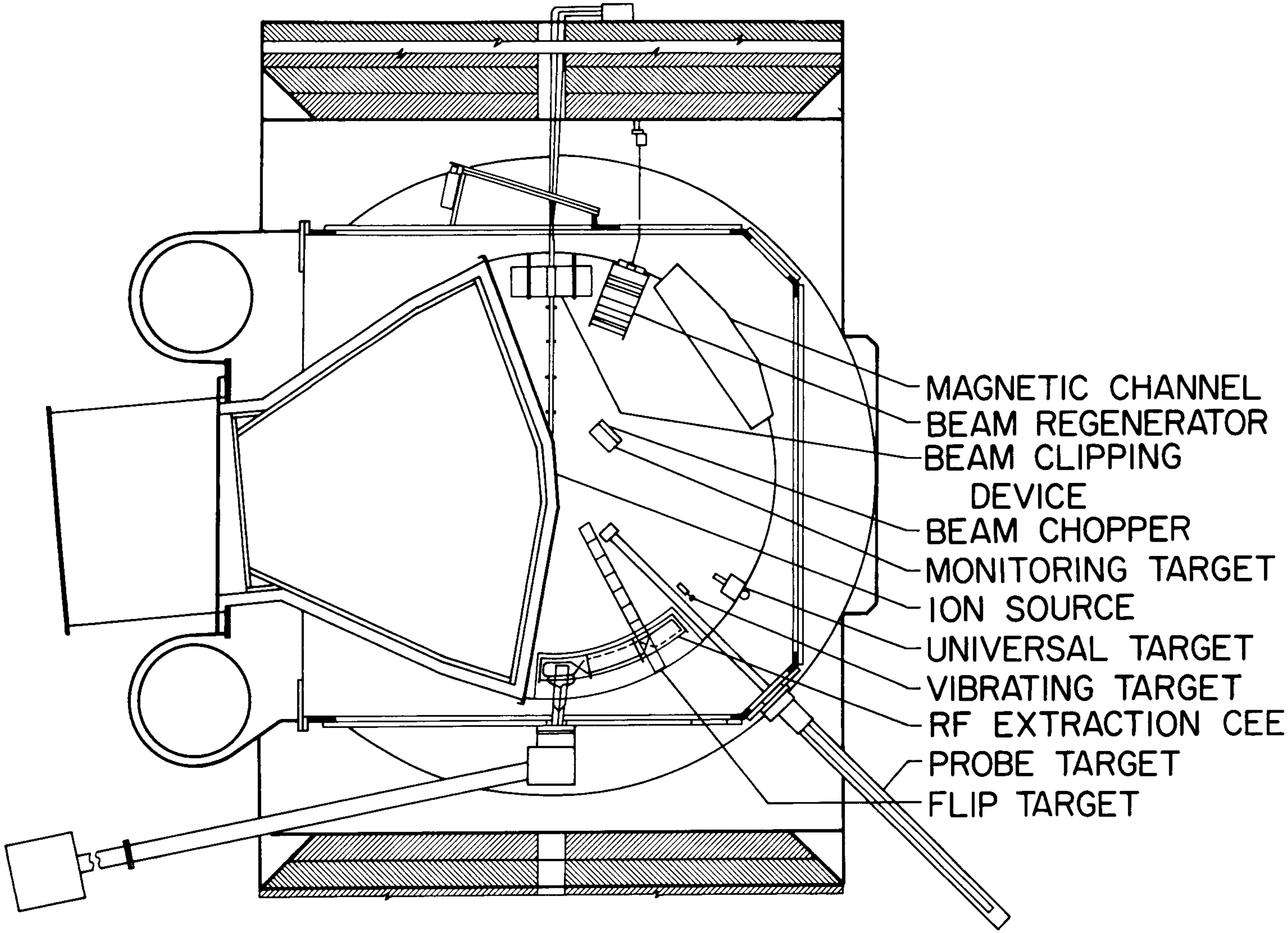


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Figure 5.- Proton Internal Target System.